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Koninklijke Philips Electronics N.V.
Groenewoudseweg 1
5621 BA Eindhoven
PAYS-BAS

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System and method for measuring properties a force

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System and method for measuring properties a force

FIELD OF THE INVENTION

The present invention relates to a system and a method for measuring properties of a force. Particularly, a gravitational force, a magnetic force, an electric force and a force due to a kinematic acceleration are subject of being measured on the basis of the present invention.

BACKGROUND OF THE INVENTION

The measuring of properties of a force, i.e. the strength and/or the orientation of the force, is an important issue in many technical fields.

For example, in several areas the orientation detection of an object with respect to gravity is desired, for instance in airplanes, virtual reality gaming, etc. An example for a method of detecting the orientation of a device is described in WO 00/00831. In this earlier publication an acceleration sensor is disclosed that includes a chamber accommodating a member made from an inductance influencing material. The member is inductively coupled to one or more coils. A force on the sensor pulls the member to a certain position in the chamber, on basis of which the self induction of the coils changes. In the absence of a movement of the chamber, the position of the member is representative of the orientation of the sensor with respect to the field of the gravity. Thus, it is possible to measure properties of the gravitational force.

Other forces to be measured are related to kinematic accelerations. Acceleration sensors, that can also be designed according to the one described with relation to WO 00/00831 are used for instance in a computer mouse, in relation to head mounted tracking, the movement tracking of body parts for virtual reality, shock sensors for air-bags, and rotation sensors for car and motor alarm.

Furthermore, it is frequently desired to measure magnetic fields. For instance, the detection of a stray field or the measuring of the strength of a certain magnet is frequently desired. Also the measuring of the earth magnetic field can be used to measure the orientation of an object relative to this field, which in turn can be used for an orientation detection in

virtual reality gaming and the other orientation related issues mentioned above. An example for a measuring device for the magnetic field is a Hall detector.

The above mentioned and other systems and methods of prior art frequently suffer from a lack of sensitivity. Also, the systems experience a mechanical wear and are costly to manufacture.

An object of the present invention is to provide a system and a method for measuring properties of a force that can be manufactured in a cost effective way, that are not subject to mechanical wear, and that are able to measure the forces with high sensitivity.

SUMMARY OF THE INVENTIOIN

The above objects are solved by the features of the independent claims. Further developments and preferred embodiments of the invention are outlined in the dependent claims.

In accordance with the present invention, there is provided a system for measuring properties of a force acting on a fluid element, the system comprising:

- a fluid element having a fluid chamber containing a first fluid (A) and a second fluid (B), the fluids being non-miscible and in contact over a meniscus, the first fluid having an index of refraction n_1, and the second fluid having an index of refraction n_2, n_1 being different from n_2,
- light source for emitting light,
- means for passing the emitted light at least partly in the direction of the fluid lens, and
- light detector means for detecting light after interacting with the fluid element, the detector means (22, 24) being capable of measuring wavefront characteristics caused by the action of the force. The wavefront characteristics can be symmetrical and/or asymmetrical.

Under several circumstances the force acting on the fluid element will lead to a deformation of the meniscus and thereby to a change of wavefront properties of the light beam that passed the fluid lens. A typical example of a symmetric wavefront change is defocus, typical examples for asymmetric wavefront changes are coma and astigmatism. Particularly, if the force is oriented along the optical axis of the fluid element, the meniscus acquires a rotational symmetric aspherical shape. This is confirmed in M. Shanahan in J. Chem. Soc. Faraday Trans. 1, 1982, vol. 78, pages 2701-2710. This results in lowest order in an optical power change of the lens and to a symmetric wavefront change. Furthermore, in

case that the force is perpendicular to the optical axis, the system acquires a "belly" giving rise to a significant amount of asymmetric wavefront change. For other orientations of the force, the meniscus has a shape in between the two mentioned shapes. The amount and sign of defocus and the amount and orientation of coma depends on the orientation and the strength of the force. Whenever the present disclosure refers to defocus, this is to be understood as an example of a symmetric wavefront change; any reference to coma is to be understood as an example for an asymmetrical wavefront change. Thus, reference to these terms is always to be understood in its most general sense. The detection of wavefront changes can be realized by various detector systems well-known in the art, e.g. by a single detector, if a sensor with a high surface resolution is used, e.g. a high resolution CCD sensor or a CMOS sensor.

The fluid element of the present invention can be realized by employing two transparant fluids. In this case the fluid element acts as a fluid lens. In particular embodiments it is also possible to employ a reflective fluid, making the fluid element acts as a fluid mirror. The reflection may be caused by a relative large difference in refractive in discs of the fluids or by a fluid with a refractive index having a complex value.

In a further example, the system is realized by comprising:

- a first light detector and a second light detector, the first light detector being arranged such that an output of the first light detector is characteristic for symmetrical wavefront changes, and
- the second light detector being arranged such that an output of the second light detector is characteristic for asymmetric wavefront changes.

Thus, cost effective measuring concepts known from error detection in optical recording can be employed.

Preferably a beam splitter is provided for splitting the light after interacting with the fluid element into a non-reflected and a reflected beam, one of the beams being directed to the first light detector and the other one being directed to the second light detector. Thus, two separated beams are available in order to separately determine defocusing and coma properties.

In this context, an astigmatic servo lens is provided and one of the beams is passed through the astigmatic servo lens to the first light detector. Since an astigmatic servo lens confers a characteristic beam spot to a defocused beam, the first light detector can be used for measuring the defocusing properties, while the second light detector that detects the reflected beam can be used to determine the coma properties.

In that sense, the present invention is particularly advantageous with relation to an embodiment wherein the light detectors are 4-quadrant detectors and wherein means are provided for generating signals by combining the intensities of the 4-quadrant detectors in a predetermined manner. The four quadrants of such of a 4-quadrant detector are sufficient in order to generate signals that are characteristic for defocus and coma, respectively. However, under certain circumstances it could be considered to use detectors with even more than four segments. The detectors used are preferably designed as CCD devices.

A preferable example of the system according to the present invention is provided by an embodiment wherein

the first detector has four quadrants a1, b1, c1, d1 detecting the intensities I_{a1}, I_{b1}, I_{c1}, I_{d1}, respectively, and the second detector has four quadrants a2, b2, c2, d2 detecting the intensities I_{a2}, I_{b2}, I_{c2}, I_{d2}, respectively,

a first signal S_1 characteristic for the defocusing of the fluid lens is generated as

$$S_1 = \frac{I_{a1} + I_{d1} - I_{b1} - I_{c1}}{I_{a1} + I_{b1} + I_{c1} + I_{d1}}$$

and

a second signal S_2 and a third signal S_3 characteristic for orthogonal coma values are generated as

$$S_2 = \frac{I_{a2} + I_{b2} - I_{c2} - I_{d2}}{I_{a2} + I_{b2} + I_{c2} + I_{d2}}$$

and

$$S_3 = \frac{I_{a2} + I_{c2} - I_{b2} - I_{d2}}{I_{a2} + I_{b2} + I_{c2} + I_{d2}}.$$

Thus, certain intensities measured from different quadrants are subtracted from intensities measured by different quadrants, and the results of these subtractions are divided by the total intensity measured by the different quadrants. Due to the particular subtracting, signals characteristic for defocusing and coma, respectively, are provided. Particularly, the signals S1, S2 and S3 can be transformed into a vector that characterizes properties of the force to be measured. This, of course, can also mean that a vector is generated that characterizes, probably besides the strength of the force, the orientation of the device into which the system is implemented.

Further, it could be advantageous to provide an embodiment, wherein

the fluid element comprises a fluid chamber having a substantially cylindrical wall, a fluid contact layer being arranged on the inside of the cylindrical wall,

means for applying an electrical field are provided comprising a first electrode separated from the first fluid and the second fluid by the fluid contact layer, and a second electrode acting on the first fluid, and

the fluid contact layer having a wettability by the first fluid which varies under the application of a voltage between the first electrode and the second electrode, such that the shape of the meniscus varies in dependence on the voltage, thereby providing a variable focus lens.

Generally, an electric field applied to the fluid lens is not required in order to practice the present invention. However, by the application of an electric field the meniscus between the two fluids can be modified so that the sensitivity for the measurement can be altered. Furthermore, a plurality of measurements can be performed with different meniscus shapes, and averages of different measurements can be generated in order to improve the accuracy.

Further, it could be advantageous to provide an embodiment, wherein

the means for applying an electrical field comprise a cylindrical electrode arrangement having several cylindrical electrodes,

various voltages can be applied to the several cylindrical electrodes, so as to correct for wavefront changes introduced by the force to be measured, and

the various voltages can be taken as a measure of the force to be measured.

In case the cylindrical electrode is split into several parallel electrodes, it becomes possible to tilt the meniscus upon application of different voltages to these electrodes. In this way it becomes possible to correct aberrations introduced by external forces. After the meniscus has been corrected, which can be checked with the detection means, the voltages are a measure for the external forces.

According to a preferred embodiment, the first fluid (A) and the second fluid (B) have different densities. Different densities make it possible to use the system in order to measure forces that are related to acceleration, whereby the physical term acceleration is to be understood in its broadest sense.

One example for this is related to an embodiment, wherein the properties of the force to be measured are the strength and the orientation of the gravitational field. For the orientation of the gravitational field, particularly the orientation of a device carrying the system according to the invention can be deducted.

Another possibility is an embodiment, wherein the properties of the force to be measured are the strength and the orientation of a kinematic acceleration. The measurement of such a kinematic acceleration can for instance be used in relation to a computer mouse, head mounted tracking, movement tracking of body parts for virtual reality and body and health monitoring, shock sensors for air-bags, and rotation sensors for car and motor alarm.

In this context it is preferable that the measuring time of the kinematic acceleration is considerably larger than a relaxation time of the meniscus. As a matter of fact, the meniscus needs a certain time to adjust to a change in acceleration. Such a relaxation time is typically of the order of 10 ms for lens sizes of 4 mm.

On the other hand, it is preferable that the measuring time of the kinematic acceleration is smaller than a time in which the acceleration is substantially constant. Otherwise, different acceleration values would be averaged which is not desired in excess to an unavoidable level.

Moreover, a measurement is discarded if subsequent samples of the measurement differ by more than by a given amount more frequently than a predetermined number of times. Thereby it is ensured that abrupt changes in the acceleration during the measurement time do not lead to erroneous measurements.

The system can advantageously be realized by an embodiment, wherein the first fluid (A) and the second fluid (B) are transparent and the light passes both fluids. Thus, a linear arrangement of the light source and fluid lens can be chosen, in which the detecting components are arranged on the light emitting side of the fluid lens.

A further advantageous system is realized by an embodiment, wherein

the first fluid (A) and the second fluid (B) have similar densities and one of the fluids is susceptible to magnetic fields and

the properties of the force to be measured are the strength and the orientation of a magnetic field.

The similarity of the densities, preferably the densities are equal, is advantageous in the sense that gravitational or acceleration effects do not impact the measurement of the magnetic field. However, it is also possible to use fluids with different densities and to measure the effects of a magnetic field. In this case one has to realize that the measured signals are influenced by several effects.

A further preferable example of the present invention is provided by a system, wherein

one of the fluids is transparent and one of the fluids is reflecting,

a beam splitter is provided for coupling the light from the light source into the optical path between the fluid lens and the detectors, and

the light passes the transparent fluid and is reflected at the meniscus to the non-transparent fluid. In this embodiment the fluid element acts as a fluid reflector.

Particularly, in relation to ferrofluids this embodiment of the invention is advantageous, since current ferrofluids are generally non-transparent.

Further, the system is useful in applications, wherein the properties of the force to be measured are the strength and the orientation of an electrical field. Since the meniscus is deformed due to the presence of an electrical field, the related force can be measured.

In accordance with the present invention, there is further provided a method of measuring properties of a force acting on a fluid element, the fluid lens having a fluid chamber containing a first fluid (A) and a second fluid (B), the fluids being non-miscible and in contact over a meniscus, the first fluid having an index of refraction n_1, and the second fluid having an index of refraction n_2, n_1 being different from n_2, the method comprising the steps:

- emitting light from a light source,
- passing the emitted light at least partly in the direction of the fluid lens, detecting the light after interacting with the fluid lens, and
- measuring wavefront changes caused by the action of the force on the basis of the detected light.

Thus, the advantages and particularities of the system according to the present invention are also realized in relation to a method. This is also applicable with relation to the preferred embodiments of the system that can be translated into preferred embodiments of the method according to the invention.

One of the most important improvements on the basis of the present invention is related to the accuracy of the measurements discussed. The results are obtained on the basis of wavefront measurements which can be preformed on a wavelength scale, hence with high precision.

These and other aspects of the invention will be apparent from and elucidated with reference to the embodiments described hereinafter.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows a schematic drawing of a system according to the invention;

Fig. 2 shows schematic drawings of a fluid lens in two different states;

Fig. 3 shows shapes of light spots on 4-quadrant detectors;

Fig. 4 shows an output signal of a 4-quadrant detector;

Fig. 5 shows a schematic set-up related to signal processing;

Fig. 6 shows a schematic drawing of a further embodiment of a system according to the present invention;

Fig. 7 shows a variable focus lens that is applicable with the present invention in schematic cross section; and

Fig. 8 shows a flow chart illustrating a preferred embodiment of a method according to the present invention.

DESCRIPTION OF PREFERRED EMBODIMENTS

Fig. 1 shows a schematic drawing of a system according to the invention. The system comprises a fluid lens 10 having a fluid chamber 12. Inside the fluid chamber 12 a first fluid A and a second fluid B are provided that are non-miscible and in contact over a meniscus 14. Due to the different indices of refraction of the fluids A, B the arrangement acts as a lens.

Light is emitted by a light source 16 and collimated by a collimator 18 so that a substantial parallel light beam is directed into the fluid lens 10. Due to the shape of the meniscus 14, the light beam is focused and therefore converging when it leaves the fluid lens 10. The converging light beam is then split by a beam splitter 26. The non-reflected part of the split beam is passed through an astigmatic servo lens 28 to a first light detector 22, while the reflected part of the beam is directed to a second light detector 24. In case of the absence of a force acting on the meniscus 14, the light beams will show substantially no defocusing and substantially no coma.

Fig. 2 shows schematic drawings of a fluid lens in two different states. In case of a force F acting on the meniscus 14 that is parallel to the optical axis of the system, the meniscus 14 will be deformed as is shown in Fig. 2a, i. e. the meniscus 14 acquires a rotational symmetric aspherical shape as shown by the solid line. The dashed line shows the form of the meniscus 14 without a force.

In case that the force acts perpendicular to the optical axis, the meniscus acquires a "belly" as shown by the solid line in Fig. 2b. The meniscus 14 without a force is again shown by the dashed line.

The state shown by the solid line in Fig. 2a leads to defocusing, and the state indicated by the solid line in Fig. 2b leads to coma. Forces in between the forces shown in Fig. 2 lead to mixed effects, i. e. to defocus and coma.

The forces on the meniscus that cause deformations as shown in Fig. 2 can be of different nature. For example, in case that the densities of the fluids A and B in the fluid chamber are different, the gravitational force will cause such deformations. Further, also with different densities of the fluids, a kinematic acceleration will have comparable effects as the gravitational force. In the case that at least one of the fluids is a ferrofluid, i. e. susceptible to the magnetic field, also a magnetic force can be the reason for deformations as shown in FIG. 2.

Fig. 3 shows shapes of light spots on 4-quadrant detectors. The light spot on the 4-quadrant detector 22 with the four quadrants a, b, c, d is characteristic for a defocused light beam that passed an astigmatic servo lens. The light spot shown on the 4-quadrant detector 24 is characteristic for a lens with coma. Thus, in case of the 4-quadrant detector 22, the intensities I_{a1}, I_{b1}, I_{c1}, I_{d1} of the four quadrants a, b, c, d, respectively, are combined to a signal S_1 in the following way:

$$S_1 = \frac{I_{a1} + I_{d1} - I_{b1} - I_{c1}}{I_{a1} + I_{b1} + I_{c1} + I_{d1}}.$$

In case of the four quadrant detector 24, the corresponding signals I_{a2}, I_{b2}, I_{c2}, I_{d2} are combined to the signals S_2 and S_3 in the following ways:

$$S_2 = \frac{I_{a2} + I_{b2} - I_{c2} - I_{d2}}{I_{a2} + I_{b2} + I_{c2} + I_{d2}},\ S_3 = \frac{I_{a2} + I_{c2} - I_{b2} - I_{d2}}{I_{a2} + I_{b2} + I_{c2} + I_{d2}}.$$

The signal S_1 is a measure for defocus and the signals S_2, S_3 are measures for the two orthogonal coma values. After calibration, these signals can be directly translated into an orientation vector of the device into which the system is implemented. Also the strength of the force can be measured on the basis of the above mentioned signals.

In case that only the gravitational field is to be measured, deviations from a constant value indicate the presence of accelerations. Thus, it can be checked whether the strength of the measured force is constant. If this is not the case, the measurement can be discarded and a new measurement can be performed in order to obtain a useful orientation detection.

Under certain circumstances and with relation to particular applications, also a kinematic acceleration can be measured on the basis of the above mentioned signals.

Fig. 4 shows an output signal of a 4-quadrant detector for an underdamped system. In the context with a kinematic acceleration it has to be considered that a certain time for the meniscus is required to adjust to the change in acceleration. Therefore, the signals must be averaged over a time period that is larger than the relaxation time of the meniscus, or the measurement should start after the relaxation time. This relaxation time of the meniscus is typically of the order of 10 ms for cell sizes of 4 mm. In Fig. 4 the relaxation time is indicated by τ_{relax}. During this time surface waves along the meniscus are present resulting in an oscillatory behavior of an output signal Δ. This output signal Δ is representative for any of the output signals S_1, S_2, S_3 mentioned above. After the relaxation time, the signal becomes substantially constant. Therefore the signal has to be averaged over a measuring time interval t_{meas}, with $t_{meas} >> \tau_{relax}$. Furthermore, t_{meas} should be chosen such that the time scale is small compared to the time the acceleration remains constant on average. Otherwise, acceleration changes that usually occur in common applications would lead to a deterioration of the measurement of a momentary acceleration.

A problem arises when a number of abrupt changes in the acceleration occur during t_{meas}. To avoid erroneous measurements, these abrupt changes are detected separately. If during a measurement more than, for example, one abrupt change occurs, this measurement can be discarded. Particularly, the problem of abrupt changes is addressed by dividing the measuring time t_{meas} in N time intervals t_{i+1}-t_i. At each time t_i a signal Δ_i is sampled. The average $\langle \Delta \rangle$ is determined by

$$\langle \Delta \rangle = \frac{1}{N} \sum_{i=1}^{N} \Delta_i$$

Further, $\delta\Delta$ is the number of times that $\Delta_{i+1} - \Delta_i$ is larger than a predefined number during the measuring time. Then $\langle \Delta \rangle$ is directly related to the acceleration and $\delta\Delta$ is equal to the number of abrupt changes in the accelerations. If for one abrupt acceleration the number $\delta\Delta$ is equal to β, β being the number of cycles occurring during a relaxation (in the present example according to FIG. 4, β=2), a measurement of $\langle \Delta \rangle$ is accepted, when

$$\frac{\delta\Delta}{\beta} \leq 2$$

Thus, the averaged values of the signals S_1, S_2, S_3 can be taken as an acceleration in the three orthogonal directions, i. e.

$$a_z = \alpha_{II}\langle S_1\rangle$$
$$a_x = \alpha_{\perp}\langle S_2\rangle$$
$$a_y = \alpha_{\perp}\langle S_3\rangle$$

wherein α are proportionality constants.

In order to improve the relaxation properties of the lens, the viscosity of the fluids can be chosen such that critical damping occurs. An example for such a fluid combination is water or a low-concentrated salt solution, e. g. 0.01M KCl having a viscosity of 1.0 cSt, and a silicone oil, e.g. polydimethylsiloxane, with a viscosity of 8.5 cSt.

Fig. 5 shows a schematic set-up related to signal processing. Here it is made clear that the signal from the sensors 30 are processed by a signal processor 32 and the signal $\delta\Delta$ is output besides the signals S_1, S_2 and S_3 in order to address the problem of abrupt changes.

Fig. 6 shows a schematic drawing of a further embodiment of a system according to the present invention. In contrast to the embodiment according to Fig. 1, the embodiment of Fig. 6 shows additionally a beam splitter 20 in the optical path between the fluid lens 10 and the detectors 22, 24. The reason for this is that instead of two transparent fluids, in the present embodiment according to Fig. 6 a transparent fluid A and non-transparent fluid B are used, wherein the meniscus 14 provides a mirror film. Thus, light emitted from the light source 10 is partly directed to the fluid lens 10, it passes through the transparent fluid A and it gets reflected by the meniscus 14. The light is then converging in direction of the detectors 22, 24 similarly as in the example according to Fig. 1.

Fig. 7 shows a variable focus lens that is applicable with the present invention in schematic cross section. The lens comprises a cylindrical first electrode 34 forming a capillary tube, sealed by a transparent front element 36 and a transparent back element 38 to form a fluid chamber 40 containing two fluids A and B. The electrode 34 may be a conducting coating applied on the inner wall of a tube.

The first electrode 34 is a cylinder of inner radius particularly between 1 mm and 20 mm. A second, annular electrode 42 is arranged at one end of the fluid chamber 40, in this case, adjacent the back element 38. The second electrode 42 is arranged with at least one part in the fluid chamber 40 such that the electrode 42 acts on the first fluid A. The electrodes 34, 42 are connected to a power supply 44 in order to supply a voltage to the electrodes, hence an electric field in the fluid chamber 40.

When a voltage is applied at the power supply port 44, the wettability of a fluid contact layer 46 by the first fluid A varies, since the first fluid A is an electrically

conducting fluid. Thus, the contact angle of the meniscus 14 changes at the line of contact between the fluid contact layer 46 and the two liquids A and B. Between the first electrode 34 and the fluid contact layer 46 an insulating layer 48 is provided. Thus, the shape of the meniscus 14 is variable in dependence on the applied voltage. In fact, the meniscus 14 can be convex or concave.

If such a lens as illustrated in Fig. 7, i. e. a lens with means for applying an electric field, is implemented in the present invention, sensitivity changes or particular measuring concepts with plural measurements at different meniscus shapes can be performed by varying the applied voltage. This can improve the quality of the measurements.

Further, in case the cylindrical electrode is split into several parallel electrodes (not shown), it becomes possible to tilt the meniscus upon application of different voltages to these electrodes. In this way it becomes possible to correct aberrations introduced by external forces. After the meniscus has been corrected, which can be checked with the detection means, the voltages are a measure for the external forces.

With respect to the difference in density that is required for the gravitation and the acceleration measurements, it is for example possible to use water as the conducting fluid with a density of 1 g/cm^3 or polyethylenglucol with a density of 1.11 g/cm^3. The density of the water may be increased by dissolving salt. For instance, a 1.95 M solution of Cs_2WO_4 has a density of 3.15 g/cm^3. For the non-conducting fluid, it is possible to use air, or rather air mixed with the vapour of the conducting fluid. Furthermore, silicone oils may be used. Densities of these oils depend on the chain lengths and vary from 0.76 to 0.98 g/cm^3. Alkanes are also very useful, for instance n-heptane with a density of 0.68 g/cm^3.

It is also possible to choose the non-conducting fluid with a higher density than the conducting fluid. For instance, the non-conducting fluid may be CCl_4 with a density of 1.59 g/cm^3, and the conducting fluid can be water or a low-concentrated salt solution, for example 0.01M KCl with a density of 1.00 g/cm^3.

Examples of ferrofluids that can be employed with the present invention are given in US 4,384,761 (Brady et al.) and references therein.

Fig. 8 shows a flow chart illustrating a preferred embodiment of a method according to the present invention. In step S01 light is emitted from the light source. The emitted light is passed through a fluid lens that can be modified by a force according to step S02 wherein the modification is particularly performed in relation to the meniscus between two fluids.

In step S03 the light is split into a reflected and a non-reflected beam.

According to step S04, the non-reflected beam is directed through an astigmatic servo lens to a first 4-quadrant detector and the reflected beam is directed to a second 4-quadrant detector.

In step S05, the signals from the first 4-quadrant detector are evaluated in order to determine properties related to defocusing.

In step S06, the signals from the second 4-quadrant detector are evaluated in order to determine properties related to coma.

In step S07 the strength of the force and/or an orientation related to the force are determined, thereby being for example able to determine the orientation of a device, the acceleration of a device and/or the properties of a magnetic field acting on the device.

It is noted that the system and the method according to the present invention can be different from the examples shown in the drawings and described above. Although, mostly it is preferable to measure only properties related to one kind of force, it is also considered to measure combinations of forces, e. g. the influence of a magnetic field and the additional influence of a kinematic acceleration. Further, the present invention is not restricted to fluid lenses of which the meniscus can move freely along the wall of the cylinder. The system also works with a meniscus "pinned" to the wall, for instance by an abrupt change in wall diameter or in the wettability of the wall. In this case, the meniscus can not move, but the meniscus will deform due to the influence of the forces discussed, thereby giving rise to wavefront changes.

Generally, it is to be noted that the term "comprising" in the present disclosure does not exclude further elements and that also the mentioning of a particular element does not exclude that a plurality of elements related to the mentioned element are present. The above embodiments are to be understood as illustrative examples of the invention.

Furthermore, equivalents and modifications not described above may also be employed without departing from the scope of the invention, which is defined in the accompanying claims.

CLAIMS:

1. A system for measuring properties of a force acting on a fluid element (10), the system comprising:

- a fluid element having a fluid chamber (12) containing a first fluid (A) and a second fluid (B), the fluids being non-miscible and in contact over a meniscus (14), the first fluid having an index of refraction n_1, and the second fluid having an index of refraction n_2, n_1 being different from n_2,
- a light source (16) for emitting light,
- means (18, 20) for passing the emitted light at least partly in the direction of the fluid element, and
- light detector means (22, 24) for detecting light after interacting with the fluid element,
- the detector means (22, 24) being capable of measuring caused by the action of the force wavefront characteristics.

2. The system according to claim 1, comprising

- a first light detector (22) and a second light detector (24),
- the first light detector being arranged such that an output of the first light detector is characteristic for symmetrical wavefront changes, and
- the second light detector being arranged such that an output of the second light detector is characteristic for asymmetric wavefront changes.

3. The system according to claim 1, wherein a beam splitter (26) is provided for splitting the light after interacting with the fluid element into a non-reflected beam and a reflected beam, one of the beams being directed to the first light detector and the other one being directed to the second light detector.

4. The system according to claim 3, wherein an astigmatic servo lens (28) is provided and one of the beams is passed through the astigmatic servo lens to the first light detector.

5. The system according to claim 2, wherein the light detectors are 4-quadrant detectors and wherein means are provided for generating signals by combining the intensities of the 4-quadrant detectors in a predetermined manner.

6. The system according to claim 5, wherein

the first detector has four quadrants a1, b1, c1, d1 detecting the intensities I_{a1}, I_{b1}, I_{c1}, I_{d1}, respectively, and the second detector has four quadrants a2, b2, c2, d2 detecting the intensities I_{a2}, I_{b2}, I_{c2}, I_{d2}, respectively,

a first signal S_1 characteristic for the defocusing of the fluid element is generated as

$$S_1 = \frac{I_{a1} + I_{d1} - I_{b1} - I_{c1}}{I_{a1} + I_{b1} + I_{c1} + I_{d1}}$$

and

a second signal S_2 and a third signal S_3 characteristic for orthogonal coma values are generated as

$$S_2 = \frac{I_{a2} + I_{b2} - I_{c2} - I_{d2}}{I_{a2} + I_{b2} + I_{c2} + I_{d2}}$$

and

$$S_3 = \frac{I_{a2} + I_{c2} - I_{b2} - I_{d2}}{I_{a2} + I_{b2} + I_{c2} + I_{d2}}.$$

7. The system according to claim 6, wherein the signals S_1, S_2 and S_3 are transformed into a vector that characterizes properties of the force to be measured.

8. The system according to claim 1, wherein

the fluid element comprises a fluid chamber having a substantially cylindrical wall, a fluid contact layer (46) being arranged on the inside of the cylindrical wall,

means for applying an electrical field are provided comprising a first electrode (34) separated from the first fluid and the second fluid by the fluid contact layer (46), and a second electrode (42) acting on the first fluid, and

the fluid contact layer having a wettability by the first fluid which varies under the application of a voltage between the first electrode and the second electrode, such that the

shape of the meniscus varies in dependence on the voltage, thereby providing a variable focus lens.

9. The system according to claim 8, wherein

the means for applying an electrical field comprise a cylindrical electrode arrangement having several cylindrical electrodes,

various voltages can be applied to the several cylindrical electrodes, so as to correct for wavefront changes introduced by the force to be measured, and

the various voltages can be taken as a measure of the force to be measured.

10. The system according to claim 1, wherein the first fluid (A) and the second fluid (B) have different densities.

11. The system according to claim 10, wherein the properties of the force to be measured are the strength and the orientation of the gravitational field.

12. The system according to claim 11, wherein the properties of the force to be measured are the strength and the orientation of a kinematic acceleration.

13. The system according to claim 12, wherein the measuring time of the kinematic acceleration is considerably larger than a relaxation time of the meniscus.

14. The system according to claim 12, wherein the measuring time of the kinematic acceleration is smaller than a time in which the acceleration is substantially constant.

15. The system according to claim 12, wherein a measurement is discarded if subsequent samples of the measurement differ by more than by a given amount more frequently than a predetermined number of times.

16. The system according to claim 1, wherein the first fluid (A) and the second fluid (B) are transparent and the light passes both fluids.

17. The system according to claim 1, wherein

the first fluid (A) and the second fluid (B) have similar densities and one of the fluids is susceptible to magnetic fields and

the properties of the force to be measured are the strength and the orientation of a magnetic field.

18. The system according to claim 1, wherein

one of the fluids is transparent and one of the fluids is reflecting,

a beam splitter is provided for coupling the light from the light source into the optical path between the fluid lens and the detectors, and

the light passes the transparent fluid and is reflected at the meniscus to the non-transparent fluid.

19. The system according to claim 1, wherein the properties of the force to be measured are the strength and the orientation of an electrical field.

20. A method of measuring properties of a force acting on a fluid element, the fluid element having a fluid chamber (10) containing a first fluid (A) and a second fluid (B), the fluids being non-miscible and in contact over a meniscus (12), the first fluid having an index of refraction n_1, and the second fluid having an index of refraction n_2, n_1 being different from n_2, the method comprising the steps:

- emitting light from a light source,
- passing the emitted light at least partly in the direction of the fluid lens,
- detecting the light after interacting with the fluid lens, and
- measuring wavefront changes caused by the action of the force on the basis of the detected light.

21. A measuring device comprising a system according to any of claims 1 to 19.

ABSTRACT:

A system and a method for measuring properties of a force acting on a fluid element (10) are provided. The fluid element contains a first fluid (A) and a second fluid (B) that are non-miscible. When a force acts on the element and deforms a meniscus (14) between the fluids, the symmetric and asymmetric wavefront characteristics of the light beam passing the fluid lens are changed. By measuring these characteristics the orientation and/or the strength of the force and other quantities related thereto can be determined.

Fig. 1

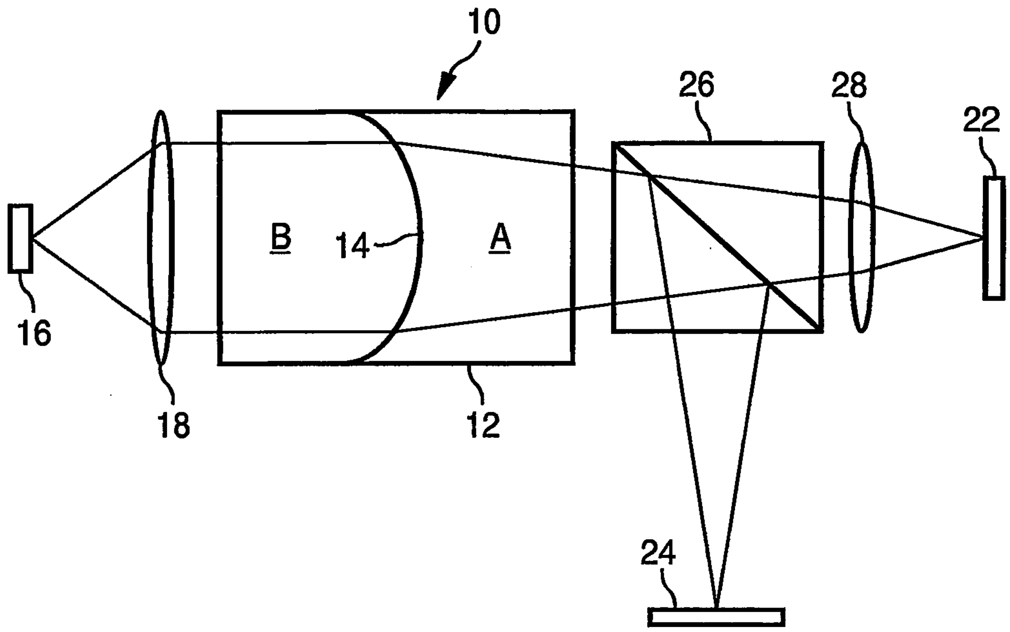

FIG.1

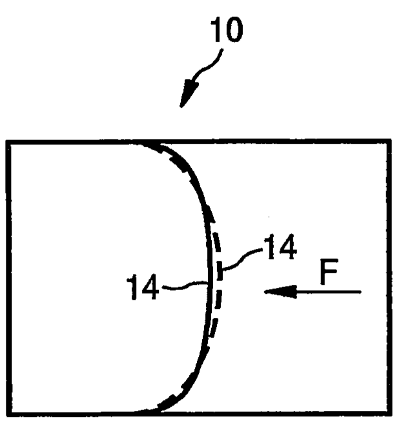

FIG.2a

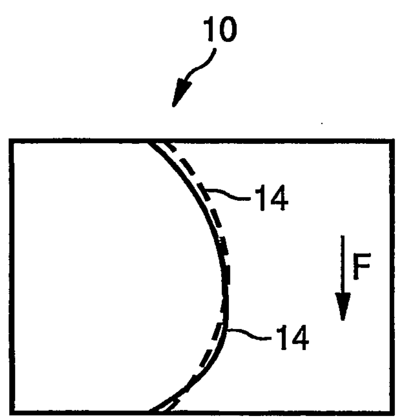

FIG.2b

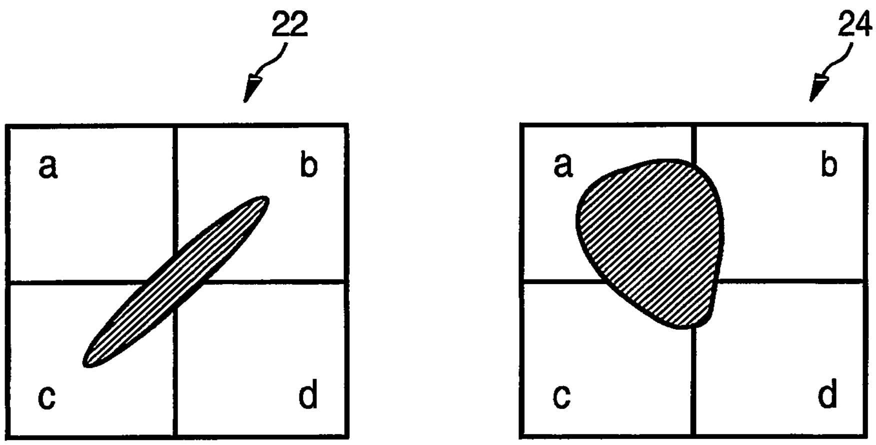

FIG.3

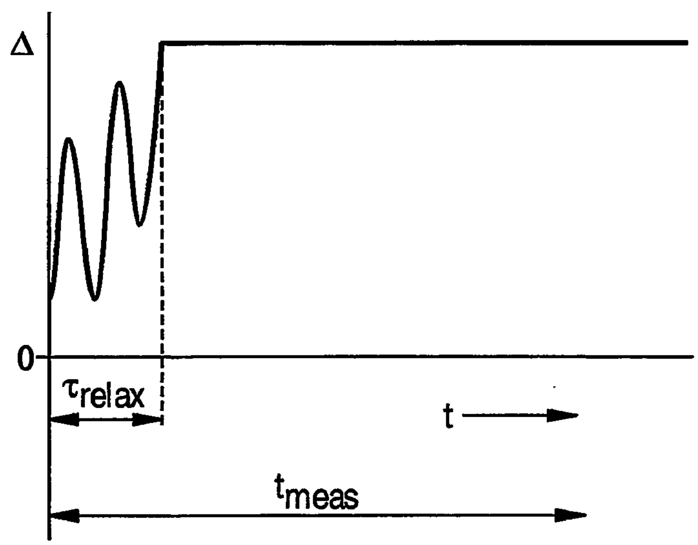

FIG.4

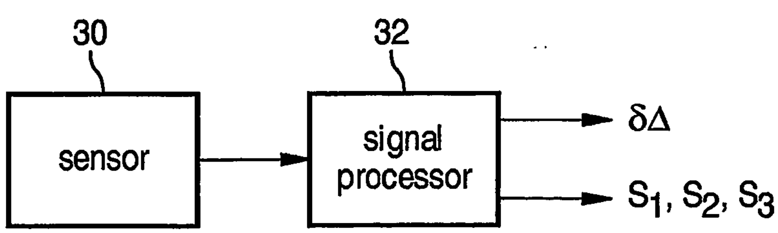

FIG.5

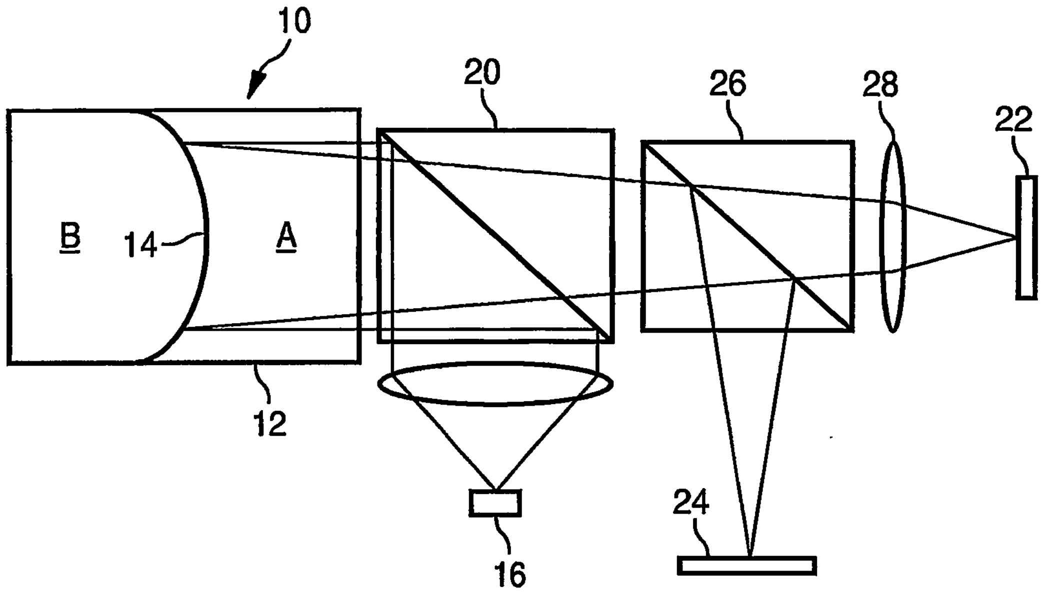

FIG.6

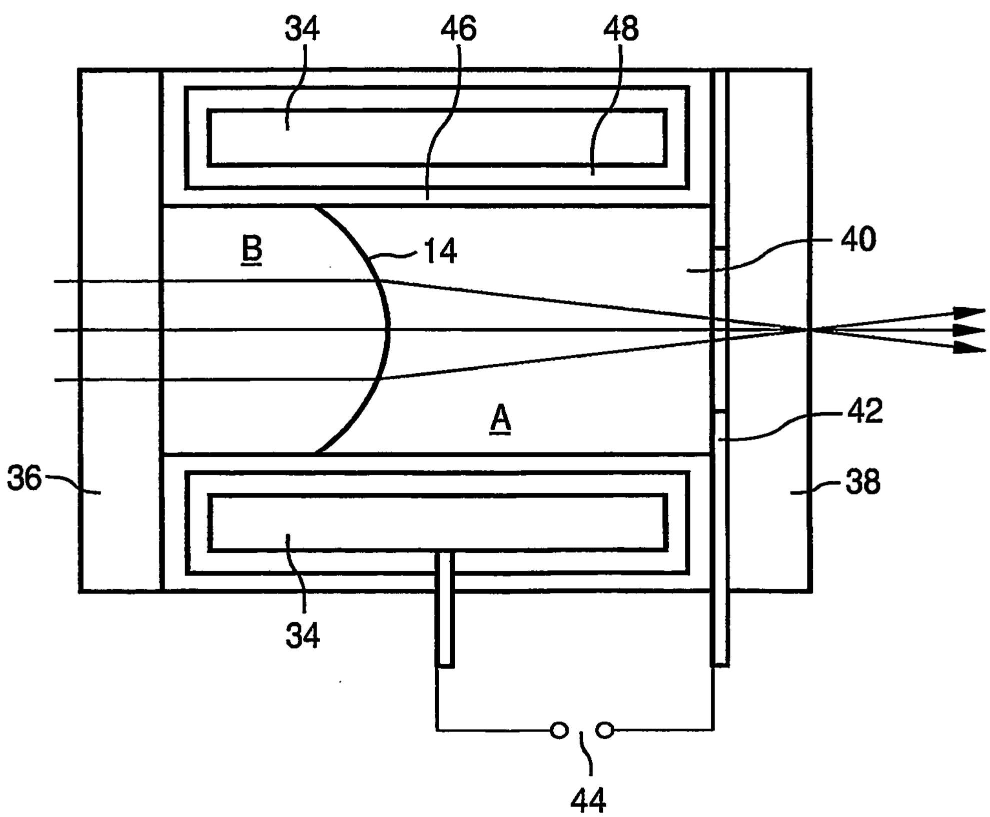

FIG.7

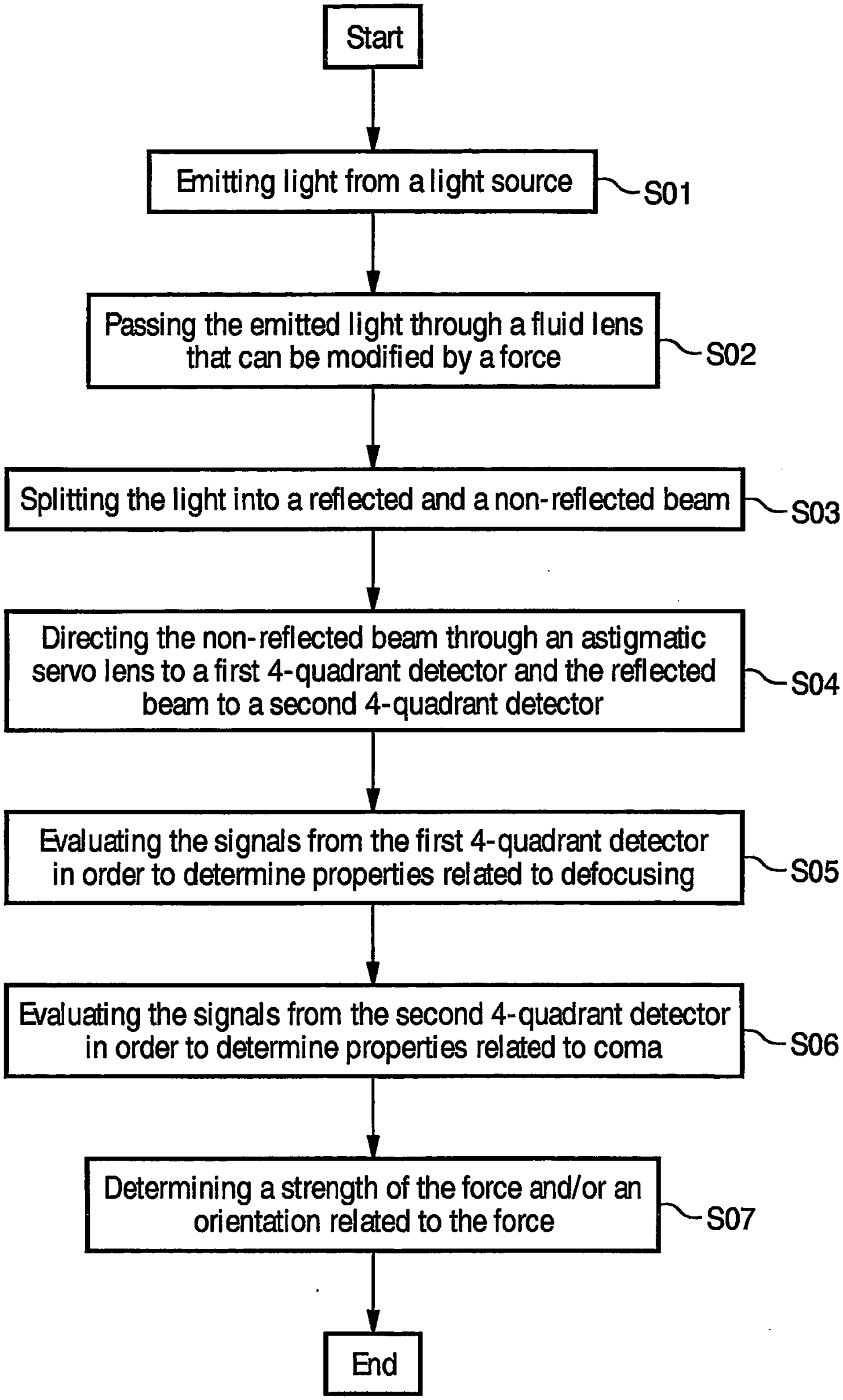
Start
Emitting light from a light source
S01
Passing the emitted light through a fluid lens that can be modified by a force
S02
Splitting the light into a reflected and a non-reflected beam
S03
Directing the non-reflected beam through an astigmatic servo lens to a first 4-quadrant detector and the reflected beam to a second 4-quadrant detector
S04
Evaluating the signals from the first 4-quadrant detector in order to determine properties related to defocusing
S05
Evaluating the signals from the second 4-quadrant detector in order to determine properties related to coma
S06
Determining a strength of the force and/or an orientation related to the force
S07
End

FIG.8

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